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Tom Briggs and Lee Wellons

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Commander
Naval Air Warfare Center Aircraft Division
22541 Millstone Road
Patuxent River, Maryland 20670-5304

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Providing precision guidance to an aircraft landing aboard a ship requires a robust and extremely accurate positioning system. Several carrier controlled approach aids (such as the AN/SPN-42A/46 Automatic Carrier Landing System) currently provide the required accuracy for the U.S. Navy. However, these systems experience reduced performance in precipitation and are difficult to maintain. A relative Global Positioning System (GPS) Kinematic Carrier Phase Tracking (KCPT) solution has the potential to provide a highly accurate solution for shipboard landing operations which is unaffected by weather.

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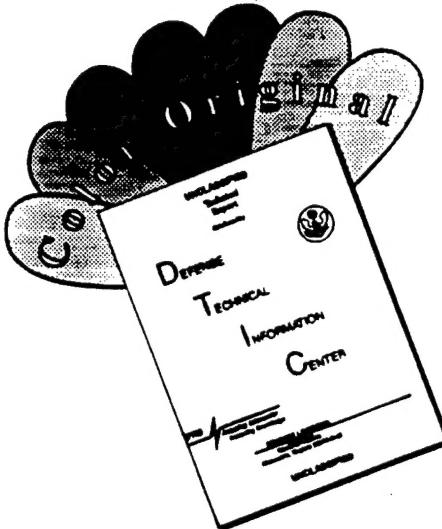
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Robust Relative All-in-View KCPT Solution for Aircraft Carrier Landing Operations

Greg Johnson, Bryce Thornberg and Phill Chesson
E-Systems
Lee Wellons and Tom Briggs
Naval Air Warfare Center Aircraft Division

BIOGRAPHY

Mr. Johnson is a Systems Engineer at E-Systems Montek Division (a Raytheon Company) in Salt Lake City, UT. He is currently developing high precision applications for GPS including precision landing and velocity measuring systems. He has been involved in GPS development and testing since 1985 as a test manager, analyst, integration engineer, and nautical surveyor. Mr. Johnson received a BSEE from Brigham Young University in 1984 and a MSEE from The Air Force Institute of Technology in 1990.

Mr. Thornberg is a Systems Engineer at E-Systems, Montek Division in Salt Lake City, Utah. He is currently project engineer for a new GPS based Air Traffic Control, Approach and Landing System being developed for the US Navy. Previously he acted as principal designer and systems analyst in the areas of antennas and propagation for microwave systems. Mr. Thornberg received a BSME and MEEE from the University of Utah in 1984 and 1989

Mr. Chesson is President of PBC Incorporated and consults on the development and analysis of Differential GPS systems. His previous positions have involved the analysis, development and integration of geographic navigation and positioning systems. Mr. Chesson holds a MS in Mathematics from Virginia Polytechnic Institute

Mr. Briggs is a Flight Test Engineer in the Air Traffic Control and Landing Systems Division of the Naval Air Warfare Center at Patuxent River, Maryland. He received a BSAE from Penn State University in 1990.

Mr. Wellons is a Systems Engineer in the Air Traffic Control and Landing Systems Division of the Naval Air Warfare Center at Patuxent River, Maryland specializing in the use of GPS for of shipboard aircraft approach and landing. He received a BSAE from North Carolina State University in 1989 and an MSEE from the Avionics Engineering Center at Ohio University in 1994.

ABSTRACT

Providing precision guidance to an aircraft landing aboard a ship requires a robust and extremely accurate positioning system. Several carrier controlled approach aids (such as the AN/SPN-42A/46 Automatic Carrier Landing System) currently provide the required accuracy for the U.S. Navy. However, these systems experience reduced performance in precipitation and are difficult to maintain. A relative Global Positioning System (GPS) Kinematic Carrier Phase Tracking (KCPT) solution has the potential to provide a highly accurate solution for shipboard landing operations which is unaffected by weather. There are several problems with a GPS based shipboard landing system over and above its shore based counterpart. The touchdown point and the GPS reference station are in motion through six degrees of freedom, the ship's dynamics are nearly as high as the aircraft dynamics (effectively doubling the bandwidth required from a navigation sensor), and the reference station experiences more cycle slips and masking due to the high electromagnetic interference environment and the ship's structure. With these considerations in mind, E-Systems, Montek Division has developed a relative, all-in-view, KCPT solution that is able to resolve and hold carrier cycle ambiguities indefinitely. Space Vehicle (SV) pseudorange and carrier phase data as well as ship's motion data are uplinked to the landing aircraft to formulate an air derived solution. The system features a floating point solution (ambiguities not resolved) and employs a Kalman filter to estimate the magnitude and covariance of the ambiguities. The results of the Kalman filter are fed to an ambiguity resolution algorithm that

operates continuously. The output of the GPS solution (either a floating or fixed solution) is blended with high rate inertial data in a filter developed by the Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River to provide a final position solution. This three step process provides a continuous navigation solution through loss and reacquisition of SVs and cycle slips. The system has been evaluated with two sets of approach and landing data. The first set was collected during an FAA Category III Feasibility Study in which E-Systems successfully completed 100 approaches and landings with a Westwind 1124 airplane using laser tracker to provide 'truth' position data. The second set was collected during a series of at-sea approaches by a GPS equipped, Naval Rotary Wing Test Squadron, SH-60F Seahawk helicopter to the aircraft carrier USS ENTERPRISE (CVN-65). The production GPS antenna (used for these tests) on the SH-60F is located in an area susceptible to SV masking and cycle slips, and the data collected during the approach profiles contained multiple occurances of both. In all cases the KCPT solution provided a seamless fixed ambiguity approach solution with an average of 42 seconds ambiguity fixing time.

INTRODUCTION

Probably the most challenging task in aviation is landing aboard an aircraft carrier. Night operations, foul weather, and pitching decks do nothing to help the situation. However the ability to launch and recover aircraft in these conditions adds to the carrier's potency. The U.S. Navy currently uses several systems to aid the pilot during landing. The AN/SPN-46 is the most capable of these. Using a shipboard precision approach radar and radio data link, the system provides both guidance needles and automatic control to aircraft equipped with a radar beacon transponder and data link receiver. The AN/SPN-41 is an pulse-code scanning beam system that provides civilian Instrument Landing System (ILS) look alike needles and is used as an independent monitor to the AN/SPN-46. In-close optical aids and a Landing Signal Officer (LSO) who monitors the approach, complete the suite of aids, and are used during all approaches. Although having supported thousands of successful landings, the AN/SPN-46 suffers some shortcomings. Only two aircraft can be provided guidance simultaneously, a transponder is required in the aircraft to achieve the required accuracy, performance can be limited in heavy rain, and the system is relatively complex to maintain.

Currently the naval aviator must rely on Precision Approach Radar (PAR) or non-precision approach aids such as TACAN at most civilian and U.S. Air Force installations. With civilian interest in GPS for shore based approaches and advances in GPS processing techniques, the Navy saw opportunities to increase shore based bad weather landing capability, reduce the amount of equipment required for landing operations, and provide a consistent set of procedures and displays for both shore based and shipboard operations. Future compatibility with civil GPS landing systems is also possible. However, the shipboard environment presents unique challenges over and above those of landing ashore. The aircraft must land in a zone approximately 20 meters long and 3 meters wide (as opposed to the several hundred meter landing box shore based), which requires decimeter accuracy from the navigation sensor. In addition, the ship (and thus the GPS reference station) translates and rotates in six degrees of freedom. Multipath effects on the reference station and SV blockage is of special concern since the environment aboard ship is dynamic, and siting relative to other stationary objects cannot be controlled. The AN/SPN-46 uses well developed techniques to compensate for the effects of ship's motion and to provide control and displays to the aircraft [1], so the first aspect addressed was providing a robust, accurate, relative position solution at a high enough sample rate to feed these stabilization and control algorithms.

A carrier phase ambiguity resolved GPS solution is the basis of the system shown herein. Differenced acceleration measurements from the aircraft and ship mitigate the low (1-2 Hz) data rate typical of GPS. GPS pseudorange and carrier phase data from the reference station as well as ship's inertial data are up linked to the landing aircraft to formulate an air derived relative position solution at 10 Hz. The ship's GPS data is up linked at 1 Hz and the ship's inertial data at 10 Hz. The GPS processing algorithm provides a continuous floating point ambiguity solution. This solution has accuracies typical of carrier smoothed code differential GPS (1-2 meters) and provides adequate accuracy for aircraft control at range. Once ambiguities are resolved, a fixed solution of higher accuracy is provided. This solution has the required accuracy for aircraft control to touchdown (less than 30 cm). Satellite switching during the ambiguity search process is addressed so outages are not experienced as long as 5 common satellites are maintained in view. The relative GPS solution and the differenced acceleration measurements are used in a blend filter to provide a high rate position, velocity, and acceleration solution to the stabilization and control equations. This blend filter uses a Kalman filter to estimate inertial measurement biases and to mitigate the latency of the GPS solution (typically one to two seconds). With better estimates of the inertial measurements, the navigation solution can be coasted through periods of GPS outages, adding to continuity of service.

The design of the KCPT software and inertial blend filter is presented along with results from two sets of data. The first set is several approaches of a Westwind 1124 turbojet to a

fixed base. The second set is shipboard approaches of an SH-60F helicopter to the USS ENTERPRISE (CVN-65).

KINEMATIC CARRIER PHASE TRACKING.

This paper describes a technology that calculates a highly accurate position solution that can survive in an aircraft carrier environment. The main component of this technology is the GPS. GPS is a satellite based navigation system that continuously transmits timing, frequency, and SV position information on the L1 and L2 channels to potential users. The full constellation consists of 24 SVs in half geosynchronous orbits. The constellation is controlled by the Department of Defense (DoD) which monitors the position and clock accuracy of the satellites. The timing information is a coded signal that allows the user to determine the time elapsed for the signal to transverse the distance between the SV and the user. By knowing the time the signal left the SV, and the speed of the signal (speed of light), the user can determine the distance from itself to the SV. This range measurement is biased by clock inaccuracies in the SV and user clocks. Because of these timing errors it is not a true range, but a "psuedorange." By knowing the position of the SV (ephemeris data), and the distance from itself to the SV, the user can triangulate its own position.

The constant motion of the SVs and possible user motion dictate that the receiver must also be able to track the change in frequency, or Doppler shift. Integration of the Doppler shift over time yields a highly accurate delta range measurement which is proportional to the advance in signal-carrier phase between two time epochs. Taking advantage of these techniques typically provides a delta range measurement to an accuracy of a tenth of the wavelength. L1 wavelength is 19 cm while L2 wavelength is 24 cm which yields an delta-range accuracy of 1-3 cm. True range between the SV and receiver cannot be determined by integrated Doppler techniques alone because the constant of integration is ambiguous. Techniques will be discussed on how these whole number ambiguities can be resolved. The interferometric concept of using integrated Doppler to resolve a relative vector between two antennas will be referred to as KCPT and involves five steps: 1) Tracking the carrier phase advance of the SV carrier signal, 2) Performing a double difference on the raw carrier phase and pseudorange measurements, 3) Solving for the relative vector between the ground antenna and airborne antenna, using double differenced pseudorange measurements, 4) Calculating a highly accurate relative vector between the air and ground antennas by resolving carrier phase ambiguities, and 5) Compensating for ship's motion and high frequency aircraft-ship kinematics with ship and air inertial data.

Carrier Phase Tracking. Once a receiver channel locks on to a carrier signal from a single SV, the channel keeps a running count of the cycles based on the Doppler shift present on L1 and L2. This is done by integrating the Doppler shift over the interval of the epoch. At the conclusion of each epoch, the estimate of the carrier phase count of that epoch is added to the count of the previous epoch to keep a running total of the number of carrier phase cycles. As long as the receiver keeps lock on the carrier, the delta-range measurement is extremely accurate. The receiver must begin to "count" or integrate at some point. When the receiver begins this count or if the receiver looses lock on the carrier, it has no knowledge of the previous Doppler shift count, so it begins to integrate at some arbitrary whole number. Therefore, the true whole number is ambiguous, and must be resolved to obtain an accurate position fix using carrier phase measurements. The methods of fixing ambiguities will be discussed later.

The conventional goal for the KCPT process is to be able to track L1 frequencies and resolve L1 ambiguities. However, L1 ambiguities are difficult to resolve because of the small L1 wavelength. Differencing L1 and L2 carrier phase measurements will produce a wide lane wavelength of 86 cm. The penalty for using the wide lane measurement is that the noise level is increased over the L1 measurement by a factor of six. Certainly, the high accuracy is obtained when L1 carrier cycle is used, but the wide lane measurement can prove as a very effective intermediate step in resolving L1 ambiguities. The Ashtech Z-12 receiver has proven effective in tracking L1 and L2 without carrier phase cycle slips that adversely effect operations. The receiver employs a Z-Code tracking capability that provides high quality code and carrier phase measurements on both L1 and L2 frequencies even with encrypted timing codes.
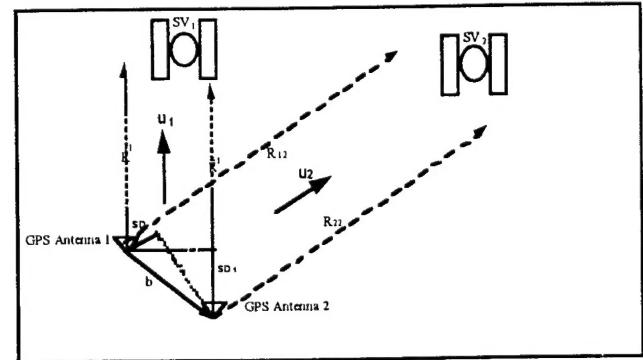

Figure 1 Double Difference Geometery

Double Difference Processing. Performing a double difference on the raw carrier phase measurements accomplishes two important tasks. It processes the range measurements so they can be readily applied to a relative vector solution, and cancels out most of the systematic errors. The KCPT solution solves for a relative vector between the ground and airborne antennas. Therefore, the

range measurements of the same SV must be differenced between the two receivers to obtain the difference in range measurements. Referring to Figure 1, two range measurements are differenced for SV_1. The vector between the two receivers is called b. By differencing the range measurement, the result is the scaler b_1, which is the dot product of the baseline vector and the unit direction vector (u_1). The unit direction vectors indicate the direction of the SVs relative to a point halfway between the ship and airborne position. This single difference is performed for all SVs in view. u_1 is assumed equal for the two receivers because the difference in unit vectors from the ground to SV and airborne to SV is negligible. This single difference virtually cancels out common errors between ground and air caused by the SV, Selective Availability (SA), and most of the atmospheric errors.

The double difference is performed by differencing the single difference of a target SV against all other SVs in view. This target SV is usually the highest elevation SV for several reasons. This choice usually yields the best geometry and tropospheric error mitigation, and the highest elevation SV will remain in view the longest, thus assuring the target SV will not have to be switched for visibility reasons during an approach. The advantage of performing the double difference is that the receiver clock errors cancel. Referring to Figure 1, it can be seen that the double difference is the dot product of true relative vector with the difference of the two unit direction vectors. In the case of pseudoranges, the double difference yields a relative range measurement with no ambiguities but significantly larger noise than the phase measurements. The carrier phase double difference measurements yields a low noise relative range measurement but with double difference ambiguities.

Pseudorange Double Difference Solution. The goal for this process is to produce a relative vector solution based on carrier phase measurements. Since the carrier phase ambiguities are still unknown, a relative position solution is not possible until the ambiguities are calculated. An initial estimate of the integer ambiguities can be performed by comparing the double differenced carrier phase measurements with the double differenced pseudorange measurements. Referring to Figure 1, an estimate of this integer ambiguity can be made by Equation 1. Since typical smoothed pseudorange double difference error has a 3σ value of 2 m, and an L1 wavelength is 19 cm, the L1 integer ambiguity can be in error $\pm$ 11 wavelengths.

$$N_I = \frac{dd_{pr12} - dd_{cp12}}{\lambda} \qquad (1)$$

where
N_I = initial estimate of double difference integer ambiguity.
dd_{pr} = pseudorange double difference between SV_1 and

SV 2.
dd_{cp} = carrier phase double difference between SV 1 and SV_2.
λ = wavelength.

The Pseudorange double difference can also be used to calculate a relative vector. This is advantageous because it can serve as a backup to the carrier phase solution if carrier phase measurements are not available. The double difference code solution can also configure the algorithms that evolve into a KCPT solution. By solving for the b vector in Equation 2, an estimate of the relative vector can be produced which should meet the shipboard accuracy requirements for a manual approach to 1/2 nmi.

Resolve Carrier Phase Ambiguities. The L1 carrier phase measurements are highly accurate measurements that can give a relative position solution to centimeter level accuracy. To accomplish this, the double difference ambiguities must be resolved. Equation 2 is expanded in equation 3 to include double difference ambiguities. Note that this process is first initialized with the ambiguities first estimated in equation 1. Once the ambiguities have been initialized they can be in error (typically less than ± 11 wavelengths). This yields 23^n possible combinations. There are several methods for resolving these ambiguities, three categories will be discussed 1) Numerical search algorithms 2) Ground based carrier phase measurements that force a high rate of change of geometry, and 3) a Kalman filter that estimates the ambiguities and covariance of ambiguities.

$$\begin{bmatrix} dd_{pr}12 \\ dd_{pr}13 \\ \vdots \\ dd_{pr}1n \end{bmatrix} = \begin{bmatrix} u_{12x} & u_{12y} & u_{12z} \\ u_{13x} & u_{13y} & u_{13z} \\ \vdots & \vdots & \vdots \\ u_{1nx} & u_{1ny} & u_{1nz} \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} dd_{cp}12 \\ dd_{cp}13 \\ \vdots \\ dd_{cp}1n \end{bmatrix} = \begin{bmatrix} u_{12x} & u_{12y} & u_{12z} \\ u_{13x} & u_{13y} & u_{13z} \\ \vdots & \vdots & \vdots \\ u_{1nx} & u_{1ny} & u_{1nz} \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} + \begin{bmatrix} N_{12} \\ N_{13} \\ \vdots \\ N_{1n} \end{bmatrix} \qquad (3)$$

where

N_{ij} = initial estimate of double difference integer ambiguity between SV I and SV j.
dd_{cpij} = carrier phase double difference between Sv_i and SV_j.
λ = initial ambiguity estimate.
u_{ij} = difference between unit vectors of SV i and j.
n = number of SVs used in the solution.

The first method to resolve carrier phase ambiguities is a numerical method using a algorithm search methodology that tries different combinations of ambiguities and examines the residuals [2]. Residuals near zero are identified and kept as a candidate ambiguity sets. The variance of these residuals are be monitored to determine the correct ambiguity set.

Another method of resolving ambiguities is to provide a ground based carrier phase measurement bubble that the aircraft will be required to fly over [3]. With the resulting fast changing geometry, the ambiguities become readily observable, and the extensive search algorithms presented in the previous paragraph are not required.

The third method employs a Kalman Filter to estimate the ambiguities. The Kalman filter uses differences in psuedorange and carrier phase double difference measurements as well as aircraft dynamics to converge on the ambiguities. A side benefit of this method is a low noise and accurate "intermediate solution" known as the float solution, that can be used while the system is resolving ambiguities. The Kalman filter alone is not as reliable as the numerical estimation approach because the Kalman only calculates the difference between the psuedorange and carrier phase measurements. Other errors caused by the atmosphere and geometry are seen by the Kalman filter as part of the ambiguity. Therefore, the Kalman filter must be augmented by a method that optimizes the three dimensional geometry of a position solution into the geometry of the current SV constellation. An effective geometry optimization method is known as the Teunissen method [4].

Inertial Blending. To provide output between the low rate (typically 1 to 2 Hz) GPS measurements, acceleration measurements from the aircraft and ship are used to extrapolate from the last valid position determined from GPS [5]. Using this technique, the stabilization and control laws can be given 10 to 20 Hz data which is adequate to track the combined ship and aircraft motion. Two consecutive GPS position solutions are used to determine an initial velocity, and the second GPS solution is used as an initial position. From these, the acceleration measurements are differenced and integrated (assuming constant acceleration over the sample time) for velocity and position propagation.

The transformation from the Earth-Centered-Earth-Fixed (ECEF) frame to the East-North-Up (ENU) frame is included in the GPS processing, so the blend filter is presented with an ENU referenced relative position vector from the ship's GPS antenna to the aircraft's GPS antenna. If different reference points are desired (for example from the ship's touchdown area to the aircraft's tailhook), moment

arm corrections for these offsets are done in the ENU frame. Thus, the offsets which are known in the body frame must be transformed to the ENU frame. This transformation uses the platform's Euler attitude measurements and is simply the product of three rotations; roll first, then pitch, then yaw [5].

$$P = \Gamma x \qquad (4)$$

Where:

Γ = is the standard Euler angle conversion matrix.
P = is the ENU oriented vector.
x = in the body axis vector

Using this rotation matrix, two moment arm corrections are applied to the relative GPS solution; the moment arm from the ship's GPS antenna to Inertial Measurement Unit (IMU) and from the aircraft's GPS antenna to IMU. This allows comparison of the relative GPS solution with acceleration measurements in subsequent processing without referencing the acceleration measurements to other points on the platform (which requires knowledge of attitude rate and attitude acceleration). If a strapdown sensor is used for measuring acceleration, the acceleration measurements are transformed to the ENU frame in the propagation of the GPS solution using the same rotation matrix above. If the accelerations are taken with a gimbaled sensor, this transformation would not be required. The following equations are used to propagate between GPS updates with body axis acceleration measurements.

$$\begin{bmatrix} E \\ \dot{E} \\ \ddot{E} \end{bmatrix}_k = \begin{bmatrix} I & dtI & \dfrac{dt^2}{2}\Gamma_{ac} & -\dfrac{dt^2}{2}\Gamma_s \\ 0 & I & dt\Gamma_{ac} & -dt \cdot \Gamma_s \\ 0 & 0 & \Gamma_{ac} & -\Gamma_s \end{bmatrix} \begin{bmatrix} E \\ \dot{E} \\ A_{ac} \\ A_s \end{bmatrix}_{k-1} \qquad (5)$$

Where

dt = time since the last propagation.
Γ = body to ENU transformation matrix.
ac = aircraft.
s = ship.
P = East North Up relative position vector.
A = body axis acceleration vector.
k = current epoch.
$k-1$ = previous epoch.
I = 3 x 3 Identity matrix.
0 = 3 x 3 zero matrix.

Given two perfect relative GPS solutions to initialize the propagation and perfect acceleration measurements, no further GPS measurements would be required. Since this is obviously not the case, some means of continuously updating the inertial propagation is needed. This process should distinguish between errors in the initial conditions for position and velocity and acceleration measurement errors. A Kalman filter is used to compare the position output of the inertial propagation with the relative GPS

solution to make this allocation. As an added benefit, the Kalman filter includes the effects of GPS measurement latency, so this latency is mitigated. The outputs of the Kalman filter are corrections to the current position and velocity in the inertial propagation (adjusting the initial conditions of future integrations) and corrections to all future acceleration measurements (the acceleration measurement bias). The only buffering requirement is that the old position outputs from the inertial propagation be saved so the output matching the GPS measurement's time can be used in forming the Kalman measurement vector.

The Kalman filter models position and velocity initial condition errors as constant. Body axis acceleration measurement errors are also modeled as constant. These are not bad assumptions since the initial condition errors are constant, and for short run times during an approach, the acceleration measurement errors are nearly constant. However, for this filter the Kalman statistics for acceleration bias are modeled as integrated white noise (or random walk).

The intent here is not to rederive the Kalman filter equations, so the measurement and state equations, (equations 6-10) are given in the standard form without further explanation.

$$z_k = H_k x_k + v_k \quad (6)$$

$$x_{k+1} = \Phi_k x_k + G_k w_k \quad (7)$$

$$z_k = \begin{bmatrix} \Delta E \\ \Delta N \\ \Delta U \end{bmatrix}_k \quad (8)$$

$$x_k = \begin{bmatrix} P_{ic} \\ \dot{P}_{ic} \\ A_{bias_{ac}} \\ A_{bias_s} \end{bmatrix}_k \quad (9)$$

$$H_k = \begin{bmatrix} I & dtI & \dfrac{dt^2}{2}\Gamma_{ac} & -\dfrac{dt^2}{2}\Gamma_s \\ 0 & I & dt\Gamma_{ac} & -dt \cdot \Gamma_s \\ 0 & 0 & \Gamma_{ac} & -\Gamma_s \end{bmatrix} \quad (10)$$

Where

P_{ic} = initial condition position error.
A_{bias} = acceleration bias vector in body axis.
dT = time since last Kalman step plus GPS latency.
G = noise transfer function.
Φ = zero if corrections are fed back.

The measurement vector (ΔE, ΔN, ΔU) is the difference in the ENU output from the inertial propagation and the relative GPS solution. Thus the filter is operating on error terms and the outputs are incremental corrections. These corrections can either be fed back to the inertial propagation (in which case the Kalman output should go to zeros) or can be accumulated and applied to the output of the inertial propagation (in which case acceleration biases cause linear growth in velocity corrections and exponential growth in position corrections). To reduce the chance of overflowing computer representations of these corrections, the outputs for position and velocity corrections are fed back to the inertial propagation, and outputs for acceleration corrections are accumulated and applied to subsequent raw acceleration measurements.

Terms in the measurement noise covariance matrix and the process noise covariance matrix are determined by the noise on the relative GPS solution and on how bias-like are the errors on acceleration measurements. Since the relative GPS solution is expected to have very low noise (any error is likely to be bias-like which the filter does not model), the diagonal terms of the R matrix ($E[vv^T]$) are relatively small (typically 5 cm or less). The nonzero diagonal terms of the Q matrix ($E[ww^T]$) have been chosen empirically at between 0.2 and 0.5 m^2/s^4 to provide reasonable estimation of acceleration measurement biases while still tracking dynamics (all non-diagonal terms in the Q matrix are set to zero). The relationship between the acceleration bias state process noise and the position and velocity initial condition noise is in the G matrix. So the terms in the Q matrix corresponding to the position and velocity error states are zero. The G matrix simply includes the effects of integrating the random walk process once for velocity noise and again for position noise [5].

Figure 2 shows the relationship between the inertial propagation and the Kalman filter in the feed-back configuration. PVA denotes position, velocity, and acceleration respectively. The 'u' subscript means uncorrected, and the 'c' subscript means corrected. Thus Pc, Vc, and Ac are the outputs that are used in the stabilization and control algorithms.
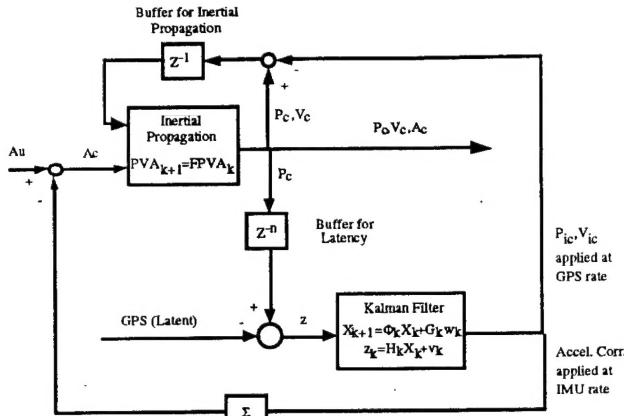
Figure 2 Inertial Propagation and Kalman Blend Filter

The Kalman gain and state covariance matrices are propagated in time with the standard equations [5][6]. The outputs of the inertial propagation should track the vehicle dynamics during the approach, and given small latency on the acceleration measurements will provide current relative position, velocity, and acceleration between the platform IMU's in the ENU frame to the stabilization and control equations. To correct for offsets between the IMU's and the desired reference points, moment arm corrections can be applied to the output of the blend filter. The position vector reference endpoints can be moved using only the moment arm vectors and the vehicle attitudes. However, to move the velocity reference requires attitude rate information, and to move the acceleration requires attitude rate and attitude acceleration information, which up to this point in the processing are not required.

Once the outputs of the blend filter are referenced to the desired points on the ship and aircraft, similar stabilization and control equations as used in the AN/SPN-46 are applied [1]. This includes ship's yaw notch filtering and low pass filtering before use in the ENU to body rotation. Ship's heave compensation will also be calculated so the aircraft's position is not controlled to match the ship's vertical motion until the last 12 seconds or so of the approach.

RELATIVE KCPT DESIGN.

The relative KCPT (RKCPT) employs the same basic concepts as the standard KCPT solution. However, there are significant differences that require an independent design of the KCPT solution. The first difference is that the touchdown point is translating in three degrees of freedom and the runway is rotating in three degrees of freedom. The second difference is that the aircraft carrier environment is hostile to the KCPT process. Multiple SV maskings and carrier phase cycle slips require a robust method to accommodate the relative fast changing SV constellation. The five design features that are unique from the standard KCPT solution are calculating the observation matrix, implementation of the Kalman Filter, ambiguity fixing

methodology, triple redundancy, and independence of the final solution from the ambiguity fixing process. The design also allows integrity checking at several points.

Observation Matrix Calculation. For the RKCPT solution, the position of the base antenna is not known, therefore the unit direction vectors are calculated by an iterative least squares method. The ground unit direction vectors are calculated and averaged with the airborne unit direction vectors to obtain the solution unit direction vectors.

Kalman Filter Implementation. The Kalman filter is the primary tool in estimating the carrier phase ambiguities. The Kalman filter estimates the aircraft dynamics as well as the floating point wide lane ambiguities. Note that this implementation estimates the wide lane ambiguities. This is done for two primary reasons. The first being that the required data up linked to the aircraft from the ship is reduced. Also, wide lane ambiguities are more readily calculated than L1 ambiguities, and wide lane accuracies should be more than adequate for shipboard approach and landing.

The Kalman filter has $8 + n$ states: Three states each for position, velocity, and acceleration plus n-1 double difference ambiguities. The variable n is the number of SVs in view. This is a straight forward implementation except for the fact that the constellation is not static. The Kalman filter must be able to change size from epoch to epoch because of SV masking and cycle slippage. Therefore, each ambiguity state must be evaluated each second to determine one of three outcomes: 1) The ambiguity state will retain the covariance information as well as the current floating point estimate of the ambiguity, 2) The ambiguity state will reset because of a cycle slip or the process has determined that the previous initialization of the ambiguity was insufficient, and 3) The Kalman filter will drop or add the ambiguity to it's states. The accordion nature of this Kalman filter is a key to the robust performance of the RKCPT process.

Ambiguity Fixing Methodology. The RKCPT method uses the Teunissen method to resolve the ambiguities. The ambiguity estimator described by P. J. G. Teunissen consists of applying a matrix transform (known as the Gauss Transform) to a set of double differenced floating point ambiguities with the aim of decoupling their statistical uncertainties. If the algorithm successfully reduces the covariances - not the pure variances - of the ambiguities, the "integer least squares" estimation of the integer ambiguities becomes much simpler and presents the system with statistically reliable integer wavelength counts.

For simplicity consider a system of just two integer ambiguities. If a_1 and a_2 represent the original estimate of

the double difference ambiguities, then the application of the simple Gauss transform,

$$\begin{bmatrix} 1 & 0 \\ \alpha & 1 \end{bmatrix} \quad (11)$$

produces the ambiguities $\underline{a}_1$ and $\underline{a}_2$ with explicit representation given by

$$\underline{a}_1 = a_1 \quad (12)$$

$$\underline{a}_2 = \alpha a_1 + a_2 \quad (13)$$

The algorithm proposed by Teunissen applies "integer least squares" estimation to this linear combinations of the original ambiguities. This operation proves successful if the transformed ambiguities $\underline{a}_1$ and $\underline{a}_2$ possess less statistical uncertainty, as indicated by their covariances, than the original ambiguities, a_1 and a_2. In that case, the problem of estimating the transformed ambiguities is more straightforward. The Gauss transform uses the more certain ambiguities to assist in the determination of the less certain ambiguities. Differing geometries of the SVs relative to the base receiver produce more or less uncertainty in the estimation of the double difference ambiguities. To retrieve the estimates of a_1 and a_2 after obtained the integer estimates of $\underline{a}_1$ and $\underline{a}_2$, we simply apply the inverse of the Gauss transform.

The whole process comprises a kind of "generalized" rounding algorithm producing integer ambiguity estimates from the input floating point ambiguities in such a way as to reduce their uncertainties. In many cases the algorithm may output some of the same integer ambiguities as would a simple rounding operation performed on the original floating point ambiguities, but even in those cases, we would have increased statistical confidence in the results by performing the Teunissen procedure. Figure 3 describes in general terms the Teunissen method
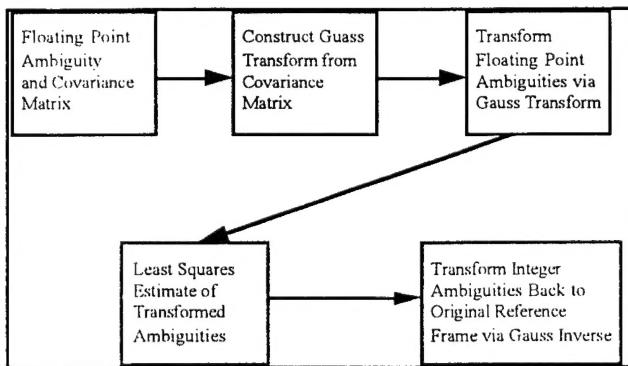

Figure 3 Generalized Teunissen Method

Triple Redundancy. The KCPT process requires a target SV to difference all other SVs against in the double difference. If a cycle slip or masking occurs on any other SV than the target SV, the process will simply reset that particular ambiguity, and the KCPT fixed solution can simply

continue without the SV in question. But if a cycle slip or masking would to occur on the target SV, then the whole ambiguity estimation process would have to be reset because every double difference ambiguity would be compromised.

This process accounts for any cycle slip by maintaining three independent RKCPT solutions which uses the first, second and third highest elevation SVs as the reference SV. If the highest elevation SV loses lock, the final RKCPT solution simply implements another set of ambiguities from another target SV. By having three independent RKCPT solutions and ambiguity estimators, there should always be fixed ambiguities available for the final approach solution.

Independent Final Solution. With the high frequency of SV maskings and cycle slips, a separation between the approach solution and the ambiguity fixing process must be maintained. The final solution only employs the ambiguities that are known to be fixed, while the Kalman filter is resolving the ambiguities that are not fixed. Therefore this process allows for the highest amount of ambiguities to be used in the final solution always anticipating the loss of SVs due to masking and cycle slips. By allowing all ambiguities that are fixed into the final solution, the availability of the fixed solution is increased.

The final relative solution is simply a least squares solution that uses the sum of the raw carrier phase double differences and either the fixed or floating ambiguities as range measurements (see Equation 3). This least squares solution also allows for the needed high rate inertial data. Inertial data from both ship and air are integrated in the manner described in the KCPT section to provide the 10 Hz solution, and to correct for GPS measurement processing latency. The results in this paper show the KCPT solution without inertial blending and singly redundant.

RESULTS.
This solution has been evaluated against two sets of actual approach and landing data. The first set of data was collected for a Category III FAA contract in which E-Systems successfully completed 100 approaches and landings with a NASA operated laser providing a truth reference. The second set of data was collected on a helicopter making several approaches to the USS ENTERPRISE (CVN-65).

FAA Category IIIb Data The RKCPT solution was used to solve several of the 100 approaches. Figures 4 and 5 show the position error compared to an Ashtech L1 generated solution known as PNAV. The Ashtech KCPT solution was checked for confidence against a NASA operated laser truth source. The solid line is the fixed solution error

truth source. The solid line is the fixed solution error magnitude while the dashed line is the error of the floating solution. Figures 6 and 7 show the ambiguity error compared to the true ambiguity for the best and worst performing fixed base approach data. We can see that in some cases the Kalman filter is able to perform very well. In the case of Figure 6, all that is required is to round to nearest ambiguity to achieve the correct ambiguity. However, in the case of Figure 7, the ambiguity never converges to the correct solution. This is the advantage of the ambiguity estimator. It allows the more certain ambiguities to help in the estimation of the less certain ambiguities.
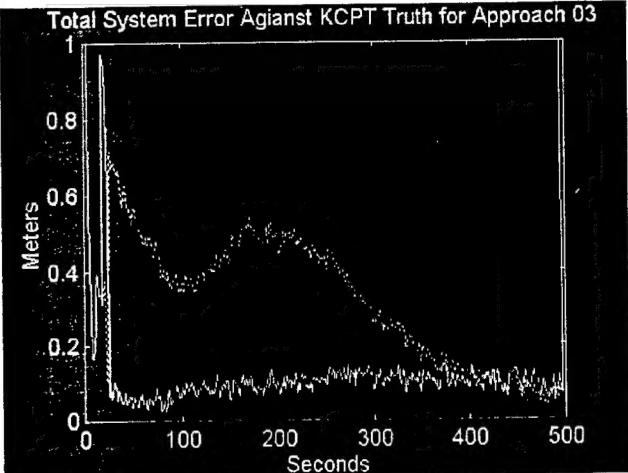

Figure 4
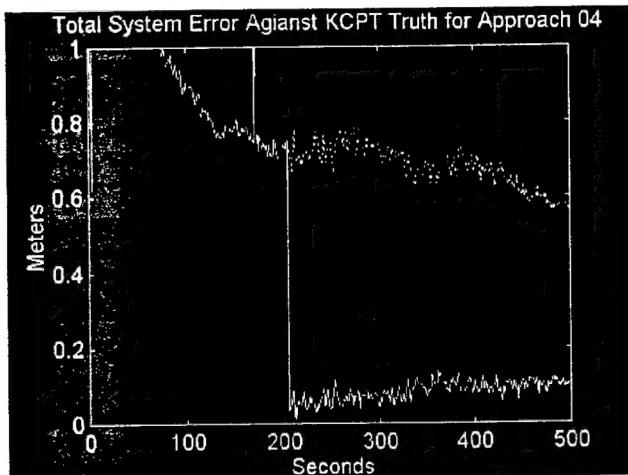
Figure 5
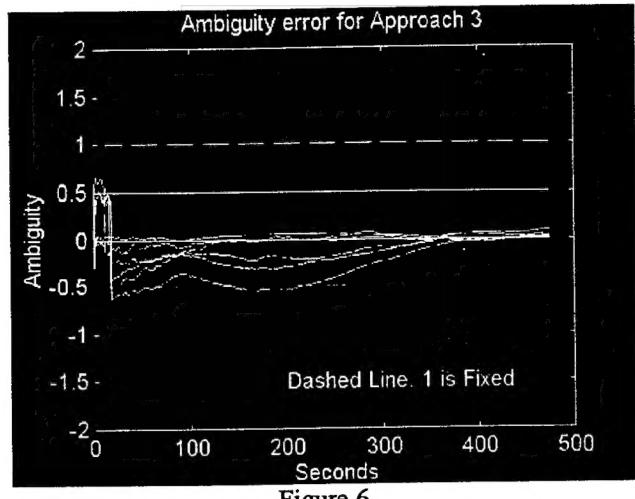
Figure 6
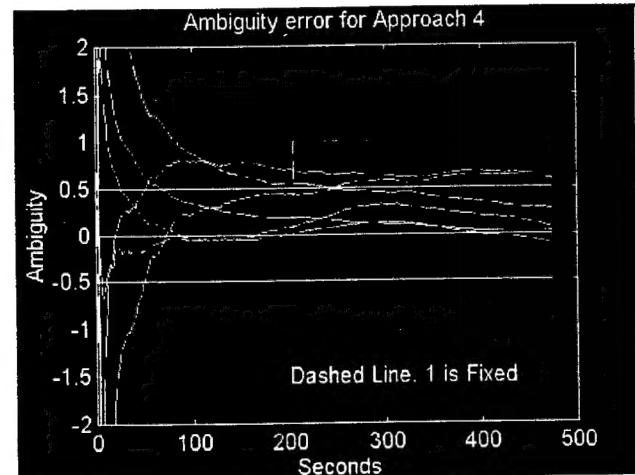
Figure 7

USS ENTERPRISE Data This analysis used thirty minutes of data collected on an SH-60 helicopter making four approaches to the USS ENTERPRISE (CVN-65). Figure 8 shows the ground trace of the Enterprise (dashed line), and the ground trace of the helicopter (solid line). The thick portion of the helicopter profile is the time that the solution was not fixed. For every approach, the solution was initialized to show that the RKCPT was able to fix ambiguities in the time allotted for a typical approach. Time to fix ambiguities for each approach was 41, 24, 109 and 21 seconds respectively. Figures 9 and 10 show the altitude and range plots with reference to time. The dashed line is high when the ambiguities are fixed. Figure 11 shows how the Kalman filter and final solution interact. The solid line is the number of SVs used in the fixed solution, the dashed dot line is the number of SV ambiguities used in the float solution, and the dotted line is the number of SVs available. It shows how the solution is constantly losing and resolving the ambiguities to give the seamless fixed ambiguity operation.
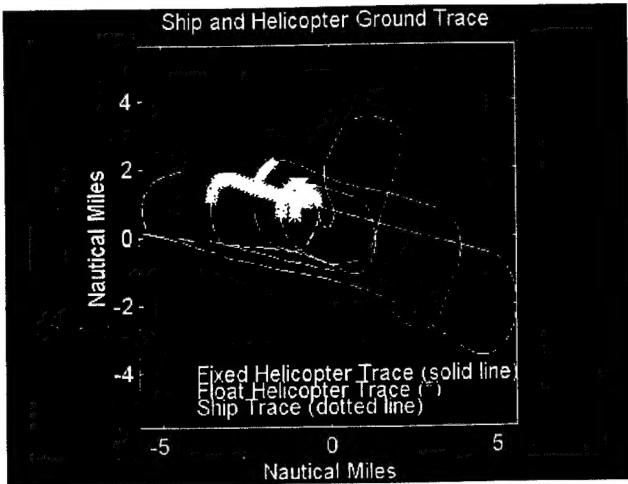
Figure 8
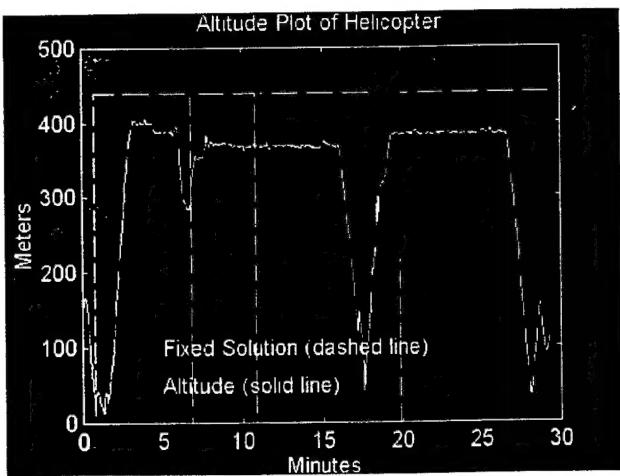
Figure 9
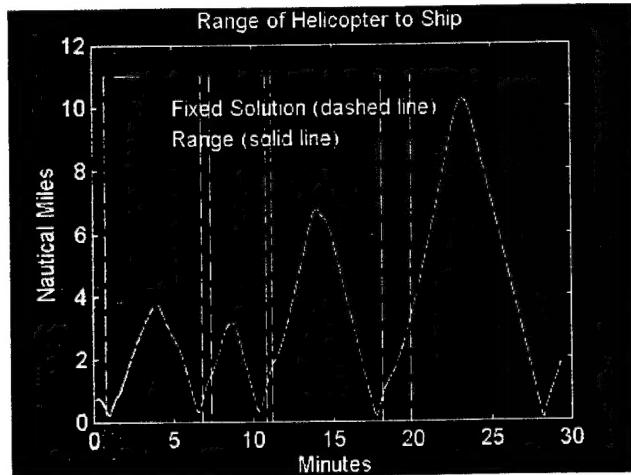
Figure 10
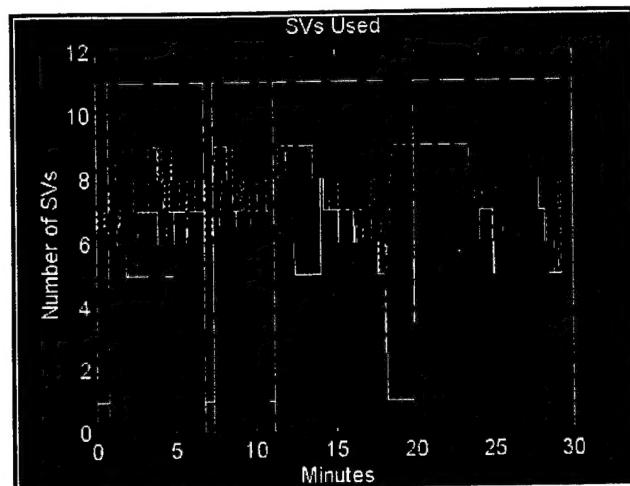
Figure 11

CONCLUSION

This method shows that is possible to employ a KCPT system aboard ship (and mobile ground stations in general) to provide precision approach and landing position solutions. To operate an RKCPT solution in a shipboard environment, the process must be able to accommodate multiple SV maskings and cycle slips on a moving platform. The test data show that the RKCPT method is able to fix and maintain carrier phase ambiguities. The next step to take in developing a GPS-based shipboard landing system is to add the inertial blend filter described above to the RKCPT solution to provide relative postion-velocity-acceleration data at an adequate rate for established precision approach display and control algorithms.

REFERENCES

[1] Central Computer Subsystem Program Perfomance Specification, Report No. 6500-944510, Revision D, Automatic Carrier Landing System AN/SPN-46, Bell Aerospace Texron, June 1983.

[2] Diggle, David, *An Investigation into the Use of Satellite-Based Positioning Systems for Flight Reference/Autoland Operations*, Doctorate Dissertation, College of Engineering and Technology, Ohio University, March 1994.

[3] C.E. Cohen, et. al., *Preliminary Results of Category III Precision Landing With 110 Automatic Landings of a United Boeing 737 Using GNSS Integrity Beacons*, Proceedings of the ION National Technical Meeting, Anaheim, CA, January 18-20, 1995.

[4] P.J.G. Teunissen, *A New Method for Fast Carrier Phase Ambiguity Estimation*, I.E.E.E Plans 94 Procedngs.

[5] Wellons, W. L., *A Shipboard Global Positioning System Carrier Phase Interferometric Aircraft Flight*

Reference System, Thesis, Ohio University, Athens, OH, November 1994.

[6] Brown, R., and Hwang, P., *Introduction to Random Signals and Applied Kalman Filtering*, John. Wiler and Sons, New York, 1992.